# High-density Particleboard Made from Agro-industrial Waste and Different Adhesives

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Particleboards were made using particles from sugarcane bagasse and eucalyptus residues of the pulp industry. The particleboard properties were evaluated according to ABNT NBR 14810-1 (2013), ABNT NBR 14810-2 (2013), and ANSI A208.1 (1999) standards, which compared the efficiency of castor oil-based polyurethane resin (PU-Castor) and urea-formaldehyde resin (UF). The particleboards were composed of 60% wood particles and 40% bagasse, with a 10% adhesive dose based on the dry mass of particles. The following parameters were evaluated: apparent density, moisture content (MC), thickness swelling after 24 h, modulus of rupture (MOR), modulus of elasticity to static bending (MOE), and internal bond strength of panels (IB). The results obtained demonstrated the potential use of eucalyptus and sugarcane bagasse residues in the production of high-density particleboards. The panels produced with PU-Castor showed greater efficiency, and their physical and mechanical properties were compatible with the requirements of the Brazilian standard for P4 panels (structural panels for use in dry conditions) and the American standard for H-3 panels (high industrial density).

*Keywords: Particleboards; Castor oil-based polyurethane adhesive; Material recycling; Eucalyptus; Sugarcane bagasse*

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## INTRODUCTION

The agro-industry involves activities that transform raw materials from agriculture, livestock, forestry, and other sectors. However, the processing of these materials generates waste that can be difficult to dispose of and has no added value. Agro-industry residues can be used in the sector of wood-based panels that are composed of lignocellulosic materials.

Much research on the development of innovative materials is underway, as consumers are increasingly concerned not only with quality and price, but also with the social and environmental impacts of products and processes (Geldermann *et al*. 2016). According to Klimek *et al.* (2018), considering the high production volumes coupled with the restrictions on the use of natural resources, a future shortage in timber supply is potentially becoming a critical issue in the forestry segment. Thus, the growing variety of lignocellulosic resources may be of strategic importance, as the use of agricultural waste as raw material certainly has economic benefits, reduces environmental burdens, and improves the efficiency of the value chain. The fact that agro-industrial waste is being incorporated into green buildings encourages the development of new environmentally friendly technologies to transform waste into products such as particleboard (Akinyemi *et al*. 2016).

According to ABNT standard NBR 14810-1 (2013), a particleboard consists of wood particles bonded with synthetic resin that are consolidated under heat and pressure. Particleboard panels have several favorable characteristics that allow their application for a variety of uses, such as in civil construction for structural or non-structural applications. (Fiorelli *et al.* 2014).

It is possible to highlight studies on the potential of using alternative materials and residues in the production of panels, such as oats bark with eucalyptus and castor oil-based polyurethane resin (Varanda *et al*. 2013), wheat straw (Bekhta *et al*. 2013), sugarcane bagasse and wood chips (Hazrati-Behnagh *et al*. 2015), sugarcane bagasse (Garzón-Barrero *et al*. 2016), rubberwood waste and castor oil-based polyurethane resin (Gava *et al*. 2015), ears of corn and sawdust (Akinyemi *et al*. 2016), rice straw (Ferrandez-Garcia *et al*. 2017), sugarcane bagasse with particles of *Pinus taeda* and Malva fibers (Silva *et al*. 2017), and textile dust (Nemli *et al*. 2019).

Considering the high annual amount of residual raw materials, such as sugarcane bagasse in countries such as Brazil, efforts should be directed to increase the valuable applications of the remaining material (Hoareau *et al*. 2006). While most research related to the manufacturing of wood composites has considered the use of chemical-based resins, new applications with greener resins based on plants, such as castor oil-based polyurethane resin, have shown promising results (Zaia *et al*. 2015).

Within this scenario, this work aims to evaluate the use of eucalyptus and sugarcane bagasse particles in the production of particleboards using and comparing two different types of adhesive, urea-formaldehyde (UF) and castor oil-based polyurethane resin (PU-Castor).

## EXPERIMENTAL

### Materials

Sugarcane bagasse (*Saccharum officinarum* L.) from a sugar and alcohol mill (Vale do Paraná S/A, Suzanápolis, Brazil) and eucalyptus residues of *Eucalyptus urophylla*, *Eucalyptus grandis*, and *Eucalyptus camaldulensis* from the mechanical processing of wood in a pulp and paper mill (Eldorado, Três Lagoas, Brazil) were used in this study. The bicomponent PU-Castor had a solids content of 100% and was composed of polyol and prepolymer (Plural Química, São Carlos, Brazil) used in a 1:1 ratio. The UF thermosetting resin (Cascamite MDF 1711; Hexion, Curitiba, Brazil) was characterized as an aqueous solution with a solids content of 58% to 62%, used with paraffin emulsion (Humocer 100 A70 TF; Isogama, São José dos Pinhais, Brazil) in the ratio of 1% to the mass of the particles, ammonium sulfate (CAS [7783-20-2]; Dinâmica, Diadema, Brazil) at the dosage of 2.5% catalyst solids relative to the solids content of the resin, and water to promote dissolution of the materials and achieve the desired moisture content for the particle mattress.

Eight homogeneous one-layer panels were produced in two treatments ($T_1$ and $T_2$). Four panels were produced for each treatment (Table 1), with dimensions of 35 cm × 35 cm × 1 cm. The panels were composed of 60% wood particles and 40% sugarcane bagasse particles. The $T_1$ treatment used UF and the $T_2$ treatment used PU-Castor. The adhesive proportion was dosed at 10% based on the dry mass of the particles.

**Table 1.** Characteristics of the Treatments

| Treatments | *Eucalyptus* (%) | Bagasse (%) | Adhesive (10%) |
|---|---|---|---|
| $T_1$ | 60 | 40 | UF |
| $T_2$ | 60 | 40 | PU-Castor |

### *Particleboard production*

The preparation of the particles took place at the Ilha Solteira School of Engineering (Ilha Solteira, Brazil). The production and testing of the panels took place at the Bauru School of Engineering (Bauru, Brazil).

The eucalyptus was processed using a knife mill (Model 5000; Trapp, Jaraguá do Sul, Brazil), and the sugarcane bagasse particles were processed *via* a vibratory sieve shaker (Model G; Solotest, São Paulo, Brazil) to adjust the dimensions. The tests to determine the particle size distribution were adapted from the standard ABNT NM 248 (2003). With the percentage of mass of particles retained and accumulated in each sieve of the vibratory sieve shaker (Model 8 × 2; Solotest, São Paulo, Brazil), the fineness modules of eucalyptus (3.7) and sugarcane bagasse (4.2) were determined. The width of the particles of eucalyptus (5.5 to 14.8 mm) and sugarcane bagasse (7.7 to 29.5 mm) were determined using a digital caliper (0.01 mm of precision).

The $T_1$ treatment particles were oven-dried (Model SL100; Solab, Piracicaba, Brazil) at 103 ± 2 °C until they reached an average moisture of 3%, while the $T_2$ treatment particles were dried outdoors (temperature 25.9 °C and humidity 85.9%) until they reached an average moisture of 10%.

After being prepared, the adhesives were added to the particles, and the homogenization took place in two steps, first manually and then mechanically, using a rotational blender (UNESP, Bauru, Brazil). The particle mattress was then prepared *via* cold pressing with a force of 5 tons using a mattress former (UNESP, Bauru, Brazil). The particle mattress was placed in a hydraulic press (Model PHH 80T; Capacity 80 t, PHS, Araraquara, Brazil) with a pressure of 50 kgf/cm$^2$ and a temperature of 100 °C for the PU-Castor and 130 °C for the UF. The samples were pressed for 10 min, with an initial pressing time of 3 min. The pressing was conducted in 30 s intervals for pressure relief to avoid the concentration of gases and consequently the formation of bubbles inside the panels, according to the method proposed by de Campos and Lahr (2004).

## Methods

### *Tests and results analysis*

After the curing and subsequent squaring of the panels, 10 specimens were removed for evaluation of each property for each treatment as defined by normative documents ABNT NBR 14810-1 and 14810-2 (2013). The density (*D*), moisture content (MC), thickness swelling after 24 h (TS), modulus of rupture (MOR), modulus of elasticity (MOE) in static bending, and the internal bond strength (IB) were evaluated.

To perform the physical tests, a digital caliper (0.01 mm of precision), an analytical scale (0.01 g of precision), and a micrometer (0.001 mm of precision) were used.

### *Determination of apparent density*

For the determination of the density, of the panels, 50 mm × 50 mm specimens were used, according to NBR 14810-2 (2013). The thickness of the specimens was measured at the point of intersection of their diagonals using the micrometer, lateral measurements were taken using the caliper, and the mass was determined with an analytical scale.

### *Determination of moisture content*

The moisture content for each treatment was determined according to NBR 14810-2 (2013), using 50 mm × 50 mm specimens. The initial mass was determined using the precision scale.

The samples were dried in the laboratory oven at 103 ± 2 °C until reaching a constant mass (*i.e.*, fluctuation between mass measurements less than 0.1%).

### *Determination of thickness swelling*

The 50 mm × 50 mm square specimens were completely submerged in deionized water at a constant temperature of 20 °C for 24 h to determine the thickness swelling of the treatments according to NBR 14810-2 (2013). The thickness swelling, measured by the micrometer, was determined by the increase in the thickness dimension after the specimens were soaked in water.

### *Determination of flexural properties*

For the determination of the MOR and MOE according to NBR 14810-2 (2013), rectangular specimens were used with dimensions of (20 × thickness + 50) mm × 50 mm. The thickness of the specimens was measured at the point of intersection of their diagonals making use of the micrometer, and the lateral measurements were made using the caliper. The specimens were placed in an EMIC universal testing machine (Model 23-300; Capacity 300 kN; INSTRON, São José dos Pinhais, Brazil) with a free span of 20 times the thickness so that the application of the load at constant speed occurred in the center of the specimen.

### *Determination of internal bond*

The internal bond strength was determined according to the NBR 14810-2 (2013) using 50 mm × 50 mm square specimens bonded to metal traction blocks with epoxy adhesive. After curing the adhesive, the assembly was fitted to the universal testing machine with constant speed load application.

The Student's *t*-test was used to statistically evaluate whether the averages of the two treatments were significantly equivalent to each other at a significance level of 5% ($p\text{-value} < 0.05$) through the statistical packages Minitab v.18 (Minitab Inc., State College, PA, USA) and Past v.3.20 (UiO, Oslo, Norway).

## RESULTS AND DISCUSSION

Table 2 shows the mean values obtained in the tests performed, compared with the values defined by ABNT NBR 14810-1 (2013) and ABNT NBR 14810-2 (2013) for P4 type panels (drywall structural panels) and ANSI A208.1 (1999) for H-1 and H-3 type panels (high density industrial).

**Table 2.** Average Results of the Physical and Mechanical Properties of the Panels

| Test | *Current Study | | ANSI (H-1) | ANSI (H-3) | ABNT (P4) |
|---|---|---|---|---|---|
| | $T_1$ (UF) | $T_2$ (PU-Castor) | | | |
| D (kg/m³) | 966 | 882 | > 800 | > 800 | 551 to 750 |
| MC (%) | 6.8 | 7.4 | < 10 | < 10 | 5 to 13 |
| TS (%) | 65.6 | 10.9 | * | * | < 19 |
| MOR (MPa) | 18 | 31 | > 16.5 | > 23.5 | > 16 |
| MOE (MPa) | 2420 | 3020 | > 2400 | > 2750 | > 2300 |
| IB (MPa) | 0.95 | 2.52 | > 0.90 | > 1.00 | > 0.40 |

*Value not referenced in this normative document; the data presented normal distribution for all tests performed

In the evaluation of the density it was observed that the panels of both treatments were high density (> 800 kg/m³), according to ANSI A208.1 (1999), exceeding the interval defined by ABNT NBR 14810-2 (2013) (551 kg/m$^3$ to 750 kg/m$^3$). The average results reached 966 kg/m³ for panels produced with UF and 822 kg/m³ for panels produced with PU-Castor. The average results of the two treatments were statistically different at 84 kg/m³, where one had 95% confidence that the true difference was between 35 kg/m³ and 134 kg/m³. The values obtained were close to those reported in the studies by Zaia *et al*. (2015), which produced panels using bamboo residues of the species *Dendrocalamus giganteus* with the castor-based polyurethane resin, reaching an average density of 912 kg/m³.

The values obtained in determining the moisture content for both treatments were in accordance with the range recommended by both the Brazilian and the American standards. The means differed statistically at the significance level of 0.05 and the difference between the samples was 0.6%, with a confidence interval between 0.3% and 1.0%.

With respect to the swelling in thickness after 24 h, the panels produced with PU-Castor reached an average value of 10.9% and for the confidence interval (8.5% to 13.3%), were within the recommended maximum value for panels of type P4 (19% according to ABNT NBR 14810-2 (2013)). The panels produced with UF reached average value of 65.6% of thickness swelling (with confidence interval of 59.1% to 72.1%) that is approximately 345% of the maximum thickness swelling value established by ABNT NBR 14810-2 (2013), which is 19%. The mean values of the UF and PU-Castor samples differed statistically 54.7%, because $p = 0.000 < 0.05$, and the confidence interval for the difference was between 48.0% and 61.4%.

According to Winandy and Morrell (2017), although the panels are generally fabricated with UF, they provide poor resistance to moisture and the resulting panels perform poorly in wet conditions, eventually undergoing deterioration in resin bonding, and loss of structural integrity. Increasing the resin content can improve the durability, but at an increased cost. This fact can explain the high values obtained in the swelling in thickness after 24 h for the panels produced with UF resin.

The average values obtained for the $T_1$ panels for MOR (18 MPa) exceeded that determined for P4 (16 MPa) and H-1 (16 MPa) panels, with 95% confidence that the mean values were between 15 MPa and 21 MPa. For panels of $T_2$, the average (31 MPa) exceeded that determined for panels of type P4 (16 MPa) and H-3 (23.5 MPa), with 95% confidence that the mean values were between 28 MPa and 34 MPa. The panels produced with PU-Castor adhesive presented an average result for MOR that was approximately 72% higher than that obtained with panels produced with UF. It was verified through statistical analysis that the means of the samples UF and PU-Castor differed statistically by 13 MPa, with the confidence interval for the difference between 9 MPa and 17 MPa.

In the work of Tabarsa *et al*. (2011), the panels produced with sugarcane bagasse had higher values of mechanical properties compared to only wood particles, with maximum MOR values of 20.5 MPa. According to the authors, the use of less dense species improved the mechanical properties of the wood composites due to the high compaction. As a comparison, the commercial panels of eucalyptus and Chinese sugarcane bagasse from the study by Oliveira *et al*. (2016) reached MOR values of approximately 13 MPa and 9 MPa, respectively. Therefore, the experimental panels developed from this study exceeded the MOR values obtained in the reference surveys and the minimum normative requirements for type P4 panels (ABNT, 2013) and H-1 (ANSI, 1999) panels.

According to ABNT NBR 14810-2 (2013) and ANSI A208.1 (1999), both treatments reached average results higher than those stipulated for type P4 panels (2300 MPa) and H-1 (2400 MPa). The panels produced with PU-Castor adhesive (3020 MPa) showed an average result approximately 25% higher than those obtained in panels produced with UF (2420 MPa), also exceeding the reference values for H-3 panels (2750 MPa). The confidence interval of the MOE for the panels produced with UF was between 1930 and 2910 MPa, against a confidence interval between 2600 MPa and 3440 MPa in the PU-Castor panels. Statistically comparing the means of the two treatments ($T_1$ and $T_2$), it was possible to conclude that they differed statistically at 600 MPa, because $p = 0.04 < 0.05$, and it was possible to have 95% confidence that the true difference was between 0 MPa and 1200 MPa. As a reference, the MOE resulting from the tests of the commercial panels of eucalyptus and Chinese sugarcane bagasse were approximately 2870 MPa and 2295 MPa, respectively (Oliveira *et al*. 2016). These values were lower than the ones determined for the $T_2$ of the present work.

It was also observed that both treatments exceeded the value defined for internal bond by the Brazilian standard for P4 panels (0.40 MPa) and American standard for H-1 panels (0.90 MPa). The panels produced with the UF resin reached an average value of 0.95 MPa, with a confidence interval between 0.80 MPa and 1.10 MPa, while the average for panels of PU-Castor was 2.52 MPa, with a confidence interval between 2.31 MPa and 2.73 MPa. The panels produced with PU-Castor showed 265% higher resistance than the panels of UF in this property, surpassing the ANSI standard A208.1 (1999) for H-3 panels (1.00 MPa). Statistically, the means of the two samples differed statistically because $p = 0.000 < 0.05$ in 1.57 MPa, the confidence interval being between 1.33 MPa and 1.81 MPa.

According to Oliveira *et al*. (2016), the internal bond values for commercial eucalyptus (0.40 MPa) and sugarcane bagasse (0.26 MPa) were much lower than those obtained in this study. According to the authors, the reason for the lower average value of internal bond for panels made from sugarcane bagasse may have been related to the lower amount of available adhesive per particle. Fiorelli *et al*. (2013) produced particleboards using PU-Castor, for which scanning electron microscopy indicated that the interparticle spaces were well filled with the adhesive, helping to improve the physical and mechanical properties of the particle panels.

## CONCLUSIONS

1. It is feasible to use agro-industrial residues to make panels of high-density particles manufactured with 60% of eucalyptus residues and 40% of sugarcane bagasse using castor oil- and UF resin-based adhesive. The results presented were compatible with the values determined by ABNT NBR 14810-1 (2013) and ABNT NBR 14810-2 (2013) standards for structural panels for use in dry conditions (P4) and ANSI standard A208.1 (1999) for high-density industrial panels (H-3), exceeding in most cases the minimum values required by the standards and those obtained in the reference literature.
2. Regarding the adhesives, the PU-Castor showed higher efficiency. In addition to achieving better mechanical results when compared to the UF resin, PU-Castor also presented better results in relation to the resistance to thickness swelling, whose result for the UF resin was not adequate. The PU-Castor adhesive was also advantageous in energy efficiency, where a lower press temperature was required because there was no need for drying in an oven, easily reaching the adequate moisture content of the particles only by exposure to the sun. Another important feature was related to the fact that the PU-Castor adhesive did not emit formaldehyde during the pressing process, making it less polluting to the environment.

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